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by C. Dewey Havill, Kenneth C. White, and Glen W. Stinnett

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A SUPERCIRCULAR ENTRY GUIDANCE CONCEPT DESIGNED FOR MAXIMUM MONITORING CAPABILITY

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SUMMARY

The reentry guidance procedure investigated permits either automatic or manual range control, and also permits the pilot to monitor the automatic system. With this procedure, it will be possible to control range from about 2,011 to 19,710 km with little reduction in entry corridor from that corresponding to vehicle capability. The automatic guidance system can be monitored with sufficient accuracy to limit skip-range errors to values which can be cancelled during the second entry for ranges less than 9,650 km and to limit overall range errors to less than 3,218 km at the maximum range. If three alternate targets are provided 805 km apart, the manual guidance procedure can be used to control to one of these targets for ranges up to 16,090 km. The results presented are limited to an Apollo type, constant-trim, roll-modulated, lifting reentry vehicle entering the atmosphere at or near escape speed, with only longitudinal range being controlled. However, nothing in the results indicates that the guidance concept could not be extended beyond these restrictions.

INTRODUCTION

Guidance of a space vehicle entering the Earth's atmosphere has been widely studied, and many specific systems have been proposed (e.g., refs. 1-4). The common procedure is to derive a set of guidance equations based on distances and velocities obtained from a stabilized inertial measuring unit (IMU). Such systems become useless if there are certain types of malfunctions in either the inertial measuring unit or associated guidance computer. For ranges greater than about 6435 km, the entry vehicle must leave the sensible atmosphere on a suborbital skip trajectory, and an error of only 1 percent in the exit velocity can result in range errors of more than 8050 km. The reliability of such a system would be improved considerably if the pilot, using information from sources independent of the IMU, could monitor the primary guidance system; particularly if, in the event of a primary guidance system malfunction, the pilot could assume control to complete the entry maneuver with acceptable accuracy.

If such a monitoring and manual guidance system is to be substantially more reliable than the primary system, it must rely on simple measurements, such as acceleration relative to a vehicle oriented coordinate system and simple guidance equipment. However, a guidance system that uses inertially fixed measurements is very difficult to monitor with a device that uses vehicle-oriented acceleration measurements. If a monitor is to detect range errors sufficiently small that they can be cancelled by subsequent manual guidance, then the primary system guidance logic must be governed by parameters that can be measured by the monitor equipment, even though, for normal guidance accuracy, the primary guidance system measures quantities that the monitor cannot. This study was directed toward finding a guidance procedure which could be governed by inputs either from an IMU or from an accelerometer strapped to the vehicle frame. It was also directed toward finding a way to monitor such a primary guidance system, and to finding a manual guidance procedure which could replace the primary system in the event of a malfunction.

The guidance procedure was developed empirically with an analog-computer simulation of a fixed-trim, roll-modulated, Apollo type reentry vehicle. Cross-range control was not considered in the study. While the system developed is suitable only for longitudinal range control of the specific type of vehicle studied, the concepts were kept sufficiently general to permit the development of similar procedures for other types of vehicles and for cross-range control.

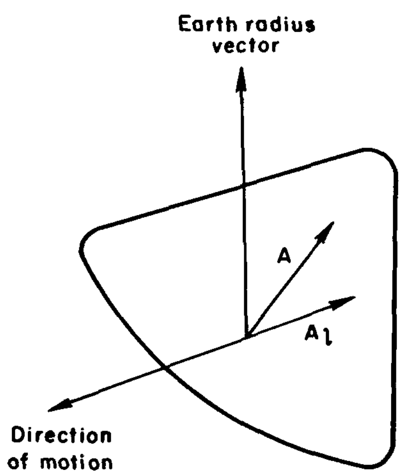
NOTATION

A	magnitude of total acceleration, g
A_l	longitudinal acceleration as indicated by a properly oriented accelerometer fixed to the vehicle, g
A_{l_R}	reference value of longitudinal acceleration, g
A_{max}	maximum negative acceleration indicated by the guide curve, g
$\dot{A}$	(dA/dt), g/sec
C_1	constant in guidance equations
D	drag, newton
f_1, f_2, f_3, f_4, f_5	functions in guidance equations
K_A	acceleration scale factor in guidance equations
K_V	velocity scale factor in guidance equations
L	component of aerodynamic lift in vertical direction, newton
n	constant in guidance equations
R_T	total range from entry point, km
R_{TG}	range to go from some trajectory point, km

δR	range correction, km
t	time, sec
δt	time increment in guidance equations, sec
V	vehicle velocity, m/sec
V_l	$\int_a A_l \, dt$, m/sec
V_o	entry velocity, m/sec
ΔV	change in velocity from entry, m/sec
ΔV_{rm}	ΔV at maximum deceleration point of guide curve
γ	flight-path angle, deg
γ_o	entry angle, deg
Φ	roll angle of vehicle, deg

Subscripts

A,B	values at points A or B of figure 1
a,b,c,d	guidance phases
max	maximum value
R	reference trace values
r	guide curve values



GUIDANCE SYSTEM DESIGN

Choice of Variables

Guidance logic for control of a reentry vehicle can be enunciated in terms of any set of four independent trajectory state variables, since four such variables are sufficient to determine a trajectory. If the state variables can be measured easily with monitoring equipment, the simplest guidance logic might be one that directly uses horizontal and vertical positions and velocities. However, to obtain such state variables the monitor sensing equipment would have to duplicate the IMU used for the primary guidance system. A more effective scheme is to develop a guidance logic based on state variables which can be measured sufficiently accurately with simple monitor sensing equipment. In normal operation of the primary guidance system, these state variables are computed accurately from the IMU output.

One of the easiest quantities to measure accurately with simple monitoring equipment is the acceleration along a line fixed in the vehicle. Since the vehicle considered in this study is a fixed-trim roll-modulated Apollo type vehicle, it is possible to accurately measure the acceleration along the flight path using a single strapped-down accelerometer (see refs. 2 and 3).

By integrating longitudinal acceleration twice with respect to time, both velocity and distance along the flight path can be found if the initial conditions are known.[1] Acceleration, velocity, and range are three of the four state variables used to control the trajectory in this study. The fourth state variable used in this sytem, the time derivative of acceleration divided by acceleration, is equivalent to the rate of change of acceleration with respect to velocity.

Figure 1 is an altitude-range plot of a typical reentry trajectory which has been marked to indicate the various guidance phases of the system being considered. The guidance phases will be discussed in detail later. A reference trajectory guidance is used during phases (a), (b), and (c), and is designed to fly the vehicle to the flight-path angle and velocity at exit required to achieve the desired skip range from B to C. Guidance during phase (d) is designed to control range to the target landing site.

Study Limitations

An analog computer simulation of an Apollo type reentry vehicle entering the atmosphere at escape speed was used to develop empirically the guidance logic outlined below. The investigation covered atmospheric entries from an altitude of 121,900 m at a velocity of 10,970 m/sec and flight-path angles at entry from -4.7° to -7.5°. The flight-path angles correspond to the capture and maximum allowable acceleration boundaries of the entry corridor. Some

[1]It is recognized that the range so computed is along the flight path and not along the earth's surface. However, for the shallow flight-path angles involved, the difference is not considered significant.

studies were made to determine the effect of variations in maximum lift-drag ratio, entry velocity, and the atmospheric density profile on guidance system performance. Range control was investigated for ranges from 2,011 to 19,710 km.

Equations from reference 5 were programmed on an analog computer to describe plane motion of a reentry vehicle over a nonrotating spherical earth. The 1959 ARDC standard atmosphere was used except for studies involving the effect of variations in atmospheric density. The following aerodynamics and control characteristics of an Apollo type reentry vehicle were programmed into the simulation. A trim lift-drag ratio of 0.5 was assumed, with its vertical component controlled by rolling the vehicle. A rate-command control system with damping feedback was used with a roll acceleration of $10^{\circ}/\mathrm{sec}^2$ and with roll rate limited to $20^{\circ}/\mathrm{sec}$. The roll rate commanded was made proportional to the difference between the vertical component of the lift-drag ratio and the desired lift-drag ratio as established by the guidance computer. The roll-rate controller was given a dead band of $\pm 1^{\circ}/\mathrm{sec}$ about the nominal null position.

General Guidance Procedure

Probably the simplest guidance procedure from the entry point A of figure 1 to the start of the skip at point B is to follow a single reference trajectory. However, possible variations in entry angle and the limited lift capability of the vehicle make this technique impossible. The difficulty is overcome, here, by dividing the guidance from A to B into phases (a), (b), and (c), corresponding to three consecutively applied guidance laws. The procedures used during these phases are identified in the monitor display for skip-range control (fig. 2). The ordinate of figure 2 is the acceleration multiplied by a scaling factor K_A, and the abscissa is equivalent to the change in velocity during phases (a), (b), and (c) multiplied by a scaling constant, K_V. The procedure during phase (a) is to guide the vehicle from the entry point (at the upper right-hand corner of fig. 2) to a point where the slope of the trace matches any one of a series of so-called guide curves. These guide curves provide possible approach paths to a reference trajectory. This trajectory terminates at point B where the vehicle has the velocity and flight-path angle required to execute a skip commensurate with the desired overall range. Guidance along the guide curve is phase (b) and along the reference trajectory is phase (c). Phases (a) and (b) may be regarded as correction periods during which the vehicle's state is adjusted to match that of some point on the reference trajectory.

The guide curves adopted here are formed from a single reference curve which has been translated along a line passing through its maximum deceleration point. The line of translation and segments of the reference guide curve in various positions, bounded by two dashed lines designated "boundaries of the guide-curve region," are shown in figure 2. (These boundaries are discussed more completely later.)

No guidance takes place during the ballistic part of the trajectory. The skip range is therefore determined by the velocity and flight-path angle at point B.

Terminal range control from point C to point D in figure 1 (phase (d) guidance) is accomplished by controlling to some point in the A-V plane where subsequent flight at constant acceleration yields a range just equal to the range to go to that point.

Phase (a) Guidance

The objective during phase (a) guidance is to adjust the slope of the trajectory trace in the acceleration-velocity plane so that at some point it is equal to the guide-curve slope. A control equation developed empirically to accomplish this objective is:

$$\left(\frac{L}{D}\right)_{a,b} = 4.0\left\{0.656 + 100\left[\left(\frac{\dot{A}}{A}\right) - \left(\frac{\dot{A}}{A}\right)_r\right] - f_1\right\} \tag{1}$$

where

$$-0.5 \leq \left(\frac{L}{D}\right)_{a,b} \leq + 0.5$$

$$f_1 = \begin{cases} K_A A + 7.5 & \text{when } K_A A + 7.5 < 0 \\ 0 & \text{when } K_A A + 7.5 > 0 \end{cases}$$

and $(\dot{A}/A)_r$ is the slope of the guide curve. The constants in equation (1) are a compromise between two opposing factors: the need to provide a high sensitivity to variations in $\dot{A}/A$ and the need to avoid overcontrolling when negative lift is required. The values were selected after flying simulated entries, using various constants, for all ranges and entry conditions of interest.

The guide curve was generated by flying constant lift trajectories for several different entry velocities and by obtaining a family of curves in the A-V plane. At each entry velocity, the entry angle was adjusted until the vehicle flight trajectory approached the reference trajectory with a slope approximately equal to the reference trajectory slope.

The guide curve is presented in figure 3. The ordinate and abscissa in figure 3(a) are related to vehicle acceleration and velocity, respectively, at the maximum deceleration point of the curve in the acceleration-velocity plane. The slope of the guide curve is shown in figure 3(b) as a function of the same relative velocity increment used as the abscissa of figure 3(a). During phase (a) guidance, the position of the guide curve in the acceleration-velocity plane is computed so that the curve passes through the point occupied by the vehicle; the scaled velocity difference between the vehicle point and the guide-curve maximum deceleration point (i.e., $K_V(9.807\int A_l \, dt - \Delta V_{rm})$ is then obtained. The curve in figure 3(b) is then used to obtain the guide-curve slope used in equation (1).

Phase (b) Guidance

The phase (b) guidance objective is to maintain the vehicle trajectory slope in the acceleration-velocity plane equal to that of the guide curve. The method used to establish the guide curve then ensures that sufficient lifting capability will be available to control to the reference trace when phase (b) guidance is ended. Phase (b) guidance differs from phase (a) guidance only because the guide curve is fixed in one position throughout this phase. Phase (b) guidance is initiated when

$$K_V\left(\Delta V_{rm} + 9.807\int A_l\,dt\right) < -\,300\,K_A A_{max} \tag{2}$$

and is ended when

$$K_V\left(\Delta V_{rm} + 9.807\int A_l\,dt\right) + 1000\,f_5 < 2250$$

where

$$f_5 = \begin{cases} K_A A + 6.5 & \text{when } K_A A < -\,6.5 \\ 0 & \text{when } K_A A > -\,6.5 \end{cases}$$

The foregoing limits have been evaluated and are designated "boundaries of guide-curve region" in figure 2. These boundaries were determined empirically for satisfactory operation of the guidance system. The position of the initial-curve boundary is not critical, and shifting its position has little effect on guidance system performance. Its position was established to provide a maximum time in phase (b) guidance for monitoring the performance of the automatic guidance system, while retaining a sufficiently large segment of the initial entry trajectory to allow the trajectory slope to be adjusted to that of the guide curve. The second guide-curve boundary position is more critical. If it is shifted much in either direction, then guidance to the reference trace is beyond the lifting capability of the vehicle.

Phase (c) Guidance

The phase (c) guidance objective is to control the vehicle trajectory in the acceleration-velocity plane so that the vehicle will leave the atmosphere at the required velocity and flight-path angle to achieve a desired skip range. This is accomplished by controlling the vehicle so that its trajectory in the acceleration-velocity plane follows the reference trace value of $K_A A_R$ as a function of $K_V\int A_l\,dt$ (fig. 4(a)). The slope of the reference trace as a function of $K_V\int A_l\,dt$ is shown in figure 4(b). The reference trajectory was a composite of trajectories which occurred in exploratory studies of other types of guidance systems. Its value of maximum deceleration is a compromise between avoiding excessive deceleration and maintaining good aerodynamic control of the flight path. Its slope, as it approaches atmospheric exit, is a compromise between accuracy of range control and aerodynamic lifting capability. The following control equation was determined empirically for satisfactory guidance system operation:

$$\left(\frac{L}{D}\right)_c = \left\{C_1\left[\left(\frac{\dot{A}}{A}\right)_R - \left(\frac{\dot{A}}{A}\right)\right] - 0.1K_A(A_R - A)\right\} f_2 - f_1 + 0.05(f_2 + 25) \qquad (3)$$

where

$$C_1 = \begin{cases} 5.0 & \text{when } \left[\left(\frac{\dot{A}}{A}\right)_R - \left(\frac{\dot{A}}{A}\right)\right] < 0 \\ 6.0 & \text{when } \left[\left(\frac{\dot{A}}{A}\right)_R - \left(\frac{\dot{A}}{A}\right)\right] > 0 \end{cases}$$

f_1 is given previously

$$100f_2 = 9.807K_V \int A_l \, dt + 5000$$

and

$$-0.4 \leq 0.0005(f_2 + 2500) \leq 0.5$$

In addition to the normal constants in equation (3) which were adjusted by trial and error, it was necessary to vary the overall sensitivity and add a variable bias with functions f_1 and f_2. The above quantities were established by trial and error to operate satisfactorily the guidance system for all ranges and entry angles considered. The variation of K_A and K_V with range is shown in figure 5.

Phase (d) Guidance

As mentioned previously, terminal range control from point C to point D in figure 1 is accomplished by controlling to some point in the A-V plane where subsequent flight at constant acceleration would cover the range to go at that point. As shown in figure 6, if a vehicle at point A were flown at a constant acceleration, $A_l = -3$ g, to the end of its trajectory, it would travel 643 km since point A is on the line with that range designation. If at point A the desired range to go were less than 643 km, the vehicle would be controlled to decrease altitude and increase decleration until a point were reached where the desired range to go equaled the range to go at constant A_l indicated on the straight lines of figure 6. If the desired range to go were greater than 643 km, the reverse procedure would be used.

The dashed lines labeled "maximum safe trace slope" indicate the steepest flight-path traces permissible if maximum vehicle deceleration is limited to 12 g. These lines are useful for both monitoring and manual guidance.

In the automatic guidance computer, the foregoing procedure is mechanized by means of the following empirical equation for phase (d) guidance:

$$\left(\frac{L}{D}\right)_d = f_3 + 30\left(\frac{\dot{A}}{A}\right) + (A_{l_R} - A_l) \qquad (4)$$

where

$$f_3 = \begin{cases} -1.0 \text{ before peak of first skip in phase (d) guidance} \\ 1.0 \text{ after peak of first skip in phase (d) guidance} \end{cases}$$

and A_{l_R} is the longitudinal acceleration found from the straight lines for the current velocity and desired range to go in figure 6. The following relationship is used to compute A_{l_R}

$$A_{l_R} = 0.00328n\left(V_o - 9.807\int_o^t A_l\,dt - 1525\text{-}1220f_4\right) + 2.0 \qquad (5)$$

where

$$f_4 = \begin{cases} 0.00497R_{TG} - 16 & \text{when } R_{TG} > 3218 \text{ km} \\ 0 & \text{when } R_{TG} \leq 3218 \text{ km} \end{cases}$$

and n is stored in the guidance computer as a function of range to go, R_{TG}. The variation of n with R_{TG} is shown in figure 7.

It was found during the guidance system tests that the final range dispersion could be considerably reduced if A_{l_R} were set equal to -7.0 g when range to go became less than 177 km; this modification was thus included in the computer. It was necessary to include the term f_4 for satisfactory operation near the borderline between skip and nonskip range-control trajectories.

Phase (d) guidance is initiated when the following conditions are satisfied:

(1) $1.75\,A_{l_R} \leq A_l$

(2) $V_o - 9.807\int_o^t A_l\,dt \leq 7925$ m/sec

After phase (d) guidance is started, it is maintained even though at some later time condition (1) may no longer be satisfied. This method of transferring control to phase (d) prohibits exit from the sensible atmosphere when it is desired to control to short ranges from the initial entry point.

A block diagram showing all phases of guidance-system operation is presented in figure 8. The various equations and control transfer logic are indicated.

Selection of K_A and K_V

Guidance from A to B of figure 1 demands a knowledge of the scale factors K_A and K_V. These quantities must be selected at the start of the reentry maneuver.

At point B, which corresponds to the end of guidance phase (c) and the start of the skip,

$$9.807K_V \int_A^B A_l \, dt = 10,000 \tag{6}$$

Since the accelerometer is fixed to the vehicle frame at an orientation which gives an accurate measure of vehicle acceleration along the flight path, equation (6) can be written with good approximation in the form:

$$K_V \left(V_B - V_o\right) = 10,000 \tag{7}$$

In addition, flight near point B is close to the fixed reference trajectory. Hence, at point B,

$$\left[\frac{d(K_A A)}{d\left(9.807K_V \int_A^B A_l \, dt\right)}\right]_B = \text{constant}$$

or

$$\frac{K_A}{K_V}\left[\frac{dA}{d(V_B - V_o)}\right]_B = \text{constant}$$

where the approximations are the same as those used for equation (7). The quantity $[dA/d(V_B - V_o)]_B$ is a function of V_B, V_o, γ_B, and the atmospheric density profile. Since the skip is ballistic, the skip range is a function of V_B and γ_B only. It follows, from equation (7), that K_V is a function of skip range, γ_B, and V_o, and from equation (8), that K_A is a function of skip range, γ_B, V_o, and the atmospheric density profile. However, if V_o is constant for all flights, as in the present study, then the factor $[dA/d(V_B - V_o)]_B$ becomes $(dA/dV_B)_B$, which depends only on conditions at point B. Thus, both K_A and K_V, in this case, are functions of skip range and γ_B only. This demonstrates a significant advantage of this guidance scheme, namely, that for fixed K_V, K_A, and γ_B, the skip range is uniquely determined and is independent of the atmospheric density profile.

If at atmospheric exit the flight-path angle γ_B is small, then range becomes excessively sensitive to errors in exit velocity. On the other hand, if γ_B is too large, the lift may be insufficient to reach this value if slight slope errors occur earlier in phase (c) guidance. Therefore, the value of γ_B must be a compromise between accuracy of range control and aerodynamic lifting capability. Once the value of γ_B has been fixed, K_A and K_V become functions of the skip range. If nominal values for the range increments from A to B and C to D are added to the skip range, K_A and K_V can be expressed as approximate functions of the total range. This functional relationship, which is fundamental to this type of guidance system, is shown in figure 5. The nominal range covered in the interval from A to B is that for which the maximum deceleration satisfies the equation:

$$K_A A_{max} = -7.0 \text{ g}$$

At entry angles (at point A) for which $K_A A_{max}$ is not -7.0 g, the range traversed from A to B differs from the nominal and an error in guidance would result if the values of K_A and K_V were selected solely on the basis of figure 5. The following equation was empirically determined to approximately correct for this type of range error:

$$\delta R = 438(K_A A_{max} + 7.0)$$

where A_{max} is the maximum deceleration on the guide curve during phase (b) guidance. The quantity δR is computed at the end of phase (a) guidance when $K_A A_{max}$ is known and updated values of K_A and K_V are determined from figure 5. The nominal value of range from point C to point D was determined by flying two entries from point C, one designed to give maximum range and one minimum range. The average of these ranges was taken to be the nominal value.

In practice, the curves of figure 5 were determined by selecting pairs of values of K_A and K_V arbitrarily and using these to simulate entries. The relative values of K_A and K_V were fixed by trial and error to make the maximum exit angle γ_B consistent with accuracy and guidance system capability.

AUTOMATIC GUIDANCE SYSTEM CAPABILITY

Guided entries were simulated for ranges from 2,011 to 19,710 km at entry angles from -4.7° to -7.5°. Some typical entry trajectories in the A-V plane are presented in figure 9 for the initial entry, and in figure 10 for the entry following the skip. Entries for desired ranges too short to permit a skip maneuver are also shown in figure 10.

The operational capability of the guidance system is indicated in figure 11, which shows the various combinations of entry angle and desired range investigated and for which the system operated satisfactorily. The feathered boundaries indicated approximate operational limits which were cursorily investigated, while the remaining boundaries merely indicate the parametric limits of the study. It is significant that, for the ranges investigated, the guidance system appears capable of operating satisfactorily over almost the entire region of vehicle capability. A more complete investigation would be expected to indicate that the actual operational boundaries of the guidance system would be approximately coincident with the vehicle capability boundaries for ranges less than 9650 km.

The effect of variations in atmospheric density was studied by separately including in the simulation the three density profiles shown in figure 12. Curve A is the 1959 ARDC standard atmosphere and curves B and C provide a variation about A. As might be expected from earlier discussions, variation of density profile apparently does not affect the overall guidance system performance, except for a minor change in the operational limits shown in figure 11. This change probably reflected, to a large degree, a change in vehicle capability.

The effect of a 10-percent variation in trim lift-drag ratio also had a negligible effect on guidance system performance, except for its effect on vehicle capability. However, the effect of changes in entry velocity was more pronounced. Reductions in entry velocity from 10,970 to 10,055 m/sec could be handled adequately by the system, but for reductions much greater than this the vehicle could not satisfactorily acquire the guide curve or reference trace. There is no apparent reason why this guidance concept could not be applied to these lower entry velocities. Such an application should only require the establishment of a new set of guidance constants and reference curves for the velocity range of interest.

MANUAL GUIDANCE SYSTEM

To control the skip range manually the pilot controls the roll angle of the vehicle so that the reentry flight path in the A-V plane first follows one of the monitor guide curves and then the reference trace. Because of undetermined differences between human and automatic pilot guidance to the exit conditions at point B, it was necessary to obtain a second set of calibrations of the factors K_A and K_V for manual operation. These factors are shown in figure 13. The values shown are for ranges greater than 6435 km only, since the short-range phase (d) type manual guidance procedure would be used for shorter ranges. In correcting total range for variations in range traversed during the first entry, as discussed previously, it was found desirable to use a manual guidance procedure different from the one used with the automatic system. This procedure consisted in using a stopwatch to measure the time, δt, required for acceleration to increase from 0.1 to 0.5 g during entry (an indirect measurement of entry angle) and making the desired range correction, δR, proportional to δt. The relationship between δR and δt is

$$\delta R = 83.7(\delta t - 10)$$

This relationship is precomputed, and the value of δR given directly on the face of the stopwatch.

For terminal range control with manual guidance the pilot observes the vehicle trajectory in the A-V plane, displayed on figure 6, and controls the vehicle in conformance with the same guidance logic used in the automatic system.

The short-range display of figure 6 is used from the initial entry conditions for the manual control of ranges less than 6435 km. The display includes the maximum negative lift (shaded region), a segment of the lowest deceleration guide curve, and all of the maximum deceleration guide curves from the skip range display. For short ranges, the pilot uses this portion of the display as he would use the skip-range display. Then reading his range to go at maximum deceleration, he chooses the appropriate reference trace for exit. Reference traces are shown in figure 6 for ranges of 3220, 4020, and 5630 km from the maximum deceleration point. Also shown is a sample trace of a piloted entry, at an entry angle of 6.5° and a desired range at entry of 6435 km.

Manual Guidance System Performance

A fixed-base piloted simulator was used in conjunction with the analog trajectory simulation to study manual range control with the guidance procedure discussed above. The pilot display panel contained an X-Y recorder with the monitor displays, a vertical gyro indicator, an accelerometer indicator, two range-to-go indicators, a stopwatch with a range scale, a manually operated range correction dial, and associated manual switches. Roll was controlled with a sidearm controller which commanded a roll rate proportional to control displacement and had the same control systems limitations as those imposed on the automatic system. A constant roll acceleration of $10^{\circ}/\text{sec}^2$ was assumed; roll rate was limited to $20^{\circ}/\text{sec}$; and a dead band of $1^{\circ}/\text{sec}$ was built into the control system. For manual entries, the pilot was given the instructions in table I. Table I also shows the pilot's comments on the guidance procedure. Typical monitor traces of manually controlled entries are presented in figures 14, 15, and 16. Figure 14 shows manual guidance for skip-range control. Figure 15 shows traces for terminal range control following skip. Figure 16 shows manual guidance for ranges less than 6435 km from the initial entry point.

Manual guidance capability subsequent to a learning period can be stated briefly as follows:

(1) For all ranges investigated, the vehicle can be guided to the target only about 70 percent of the time.

(2) If maximum range is limited to 16,090 km, the vehicle can be guided to the target 80 percent of the time.

(3) If two alternate targets are defined 805 km ahead of and 805 km behind the primary target, then, for all ranges investigated, the vehicle can be guided to one of the three targets 95 percent of the time.

(4) With two alternate targets as in (3), if maximum range is limited to 16,090 km, this study indicates that the vehicle can be guided to one of the three targets 100 percent of the time.

The foregoing statements apply to all entry angles for which satisfactory operation is achieved with the automatic guidance system.

MONITORING PROCEDURE

One of the more attractive features of the guidance system is that it can be monitored. Since the automatic system has been designed to use the same basic guidance logic that a pilot would follow manually on the two monitor displays, the pilot can observe these displays during automatic system operation and determine whether the guidance rules are being obeyed. Specific rules that permit a pilot to detect primary-system malfunctions are as follows:

(1) During phase (a) guidance, the system must operate at $\pm(L/D)_{max}$ in either of the shaded regions (see fig. 2).

(2) The flight trace must not move one guide-curve space during phase (b).

(3) After leaving the guide-curve region, the flight trace must always approach the reference trace until it enters the shaded reference-trace region.

(4) After entering the shaded reference-trace region, the flight trace must never leave that region.

Examples of violations of rules (2), (3), and (4) are shown in figure 17.

The monitoring procedure was tested by imposing various magnitude errors on the automatic guidance-system measurements and logical operations, and determining the maximum range error which would occur before the error was detected using the foregoing monitor rules. Except for the maximum range condition (R_T = 19,710 km), errors that occurred during guidance phase (a) or (b) were detected well before they could result in a skip-range error which could not be corrected during the second entry. However, undetected errors during phase (c) guidance led to larger skip-range errors and appeared to establish the monitoring limit for the system. The magnitude of maximum skip-range error undetected by the monitor is established by the width of the shaded region on each side of the reference trace, since this width establishes the maximum velocity error at the initiation of skip. The width of the shaded area was established empirically so that it would contain the flight traces for the entire region of guidance-system operation shown in figure 11, when no errors were present. Using more sophisticated design techniques, this width might be appreciably diminished. However, for the present width, the maximum skip-range error has been computed by determining range as a function of exit velocity and then permitting exit velocity to vary by a value equal to the width of the shaded area. This variation of maximum skip-range error is presented in figure 18 along with the approximate range variation available during the second entry. Figure 18 indicates that, for ranges less than 9,650 km, any error not detected by the foregoing monitor rules can be cancelled during the second entry. It also indicates that, at the maximum range of 19,710 km, the maximum final-range error undetected on the monitor is less than about 3,218 km.

Monitoring during phase (d) guidance was not investigated because neither the range error nor the safety problems were large during this guidance phase.

It is obvious that a pilot would monitor the maximum descent angle of the flight trace to avoid excessive deceleration, using the dashed curves of the monitor display for this purpose. Range monitoring is also inherent in the display and only requires development.

CONCLUDING REMARKS

A guidance procedure has been proposed which can be used with either an automatic or manual control system, and which can be monitored by a pilot when used in the automatic mode. A simulation study of the system's operating characteristics indicated the following conclusions:

(1) The automatic guidance system will satisfactorily control ranges from 2,011 to 19,710 km and for almost the complete corridor of entry angles that vehicle capability will permit.

(2) Satisfactory range control is achieved with the manual guidance system for ranges less the 16,090 km when three landing sites 805 km apart are provided.

(3) The automatic guidance system can be monitored with sufficient accuracy to limit skip-range errors to values which can be cancelled (during the second entry) for ranges less than 9,650 km, and to limit overall range errors to less than 3,218 km for a range of 19,710 km.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 25, 1966
125-17-05-02

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TABLE I.- PILOTING INSTRUCTIONS AND PILOT'S COMMENTS

Skip Guidance	
Piloting instructions	Pilot's comments
Pre-Guide-Curve Region (1) In max negative (L/D) area, maintain $\varphi = 180^\circ$ until trajectory will cross edge of region 1/2 inch away; then roll to $\varphi = 90^\circ$. (2) Outside of max negative (L/D) area, maintain slope of max positive (L/D) area boundary. (3) As guide curves are approached, roll to $\varphi = 90^\circ$ unless a large error in trajectory slope is present.	The entries were initiated with $\varphi = 90^\circ$, and at $A = 0.1$ g, the vehicle was rolled to either $\varphi = 0^\circ$ or $\varphi = 180^\circ$, depending on the elapsed time from entry (121,900 m altitude) to $A = 0.1$ g. $\varphi = 0^\circ$ was used for elapsed times less than 30 sec. This procedure made the piloting task easier for entry angles near the corridor limits.
Guide-Curve Region (1) Trajectory slope should be almost equal to guide-curve slope, but should be slightly steeper during latter half of region. (2) If guide curves are crossed, do not attempt to return to starting guide curve, but adjust to slope of nearest one. (3) Unless a large slope error occurs, maintain φ between 60° and 120° in guide-curve region.	A nominal bank-angle variation which will make the task easier is $\varphi = 90^\circ$ at entry to the guide curve region, decreasing slowly to $\varphi = 10^\circ$ when acceleration has decreased to 4 g. Following this, $\varphi = 125^\circ$ appears to be a good nominal value. Since trajectory control is more effective at the higher g levels, it is desirable to acquire the reference trajectory as early as possible. It is essential that, as soon as departure from the nominal trajectory slope is observed, a large correction of about 60° be made, and then about half of it removed immediately. As the task is learned better, discrepancies will be sensed earlier and smaller corrections will suffice. Considerable improvement in guidance would result if control power were increased. Do not agree with suggestion 1, because allowing trajectory to become steeper than guide curve near end at low accelerations can place vehicle in position in A-V plane from which it is difficult to control to final reference trajectory conditions.

TABLE I.- PILOTING INSTRUCTIONS AND PILOT'S COMMENTS - Concluded

Piloting instructions	Pilot's comments
Skip Guidance	
Post-Guide-Curve Region (1) Achieving and maintaining reference trajectory slope is most important objective. (2) In shaded region, if trajectory slope is as steep as reference slope, use negative lift. (3) If slope is steeper, use maximum negative lift. (4) If and when it becomes obvious that exit conditions cannot be achieved, continue to control in an effort to achieve them. This mode of control will compensate for mission exit point.	
Short-Range Guidance	
(1) Range is controlled by flying to a point where the R_{TG} meter reads the same as the value shown on the display and then maintaining constant acceleration. (2) Since constant accelerations cannot be maintained less than about 1.5 g, when operation in this region is desired, maintain full lift at all times until the desired operating acceleration is greater than 2 g. (3) When R_{TG} meter indicates 121 km, roll to $\varphi = 180^{\circ}$ and pull out at $A_l = 6$ g and maintain thereafter. If acceleration is decreasing, roll at $R_{TG} = 129$ to 145 km. If acceleration is increasing, roll at $R_{TG} = 97$ to 113 km. (4) Dashed curves indicate maximum trajectory slope to avoid excessive accelerations. Do not permit trajectory to become steeper than these curves.	When second entry becomes apparent ($A \neq 0$), range to go should be between 1207 and 3057 km. For all but the shortest ranges, maximum lift should be maintained through the first peak in altitude.

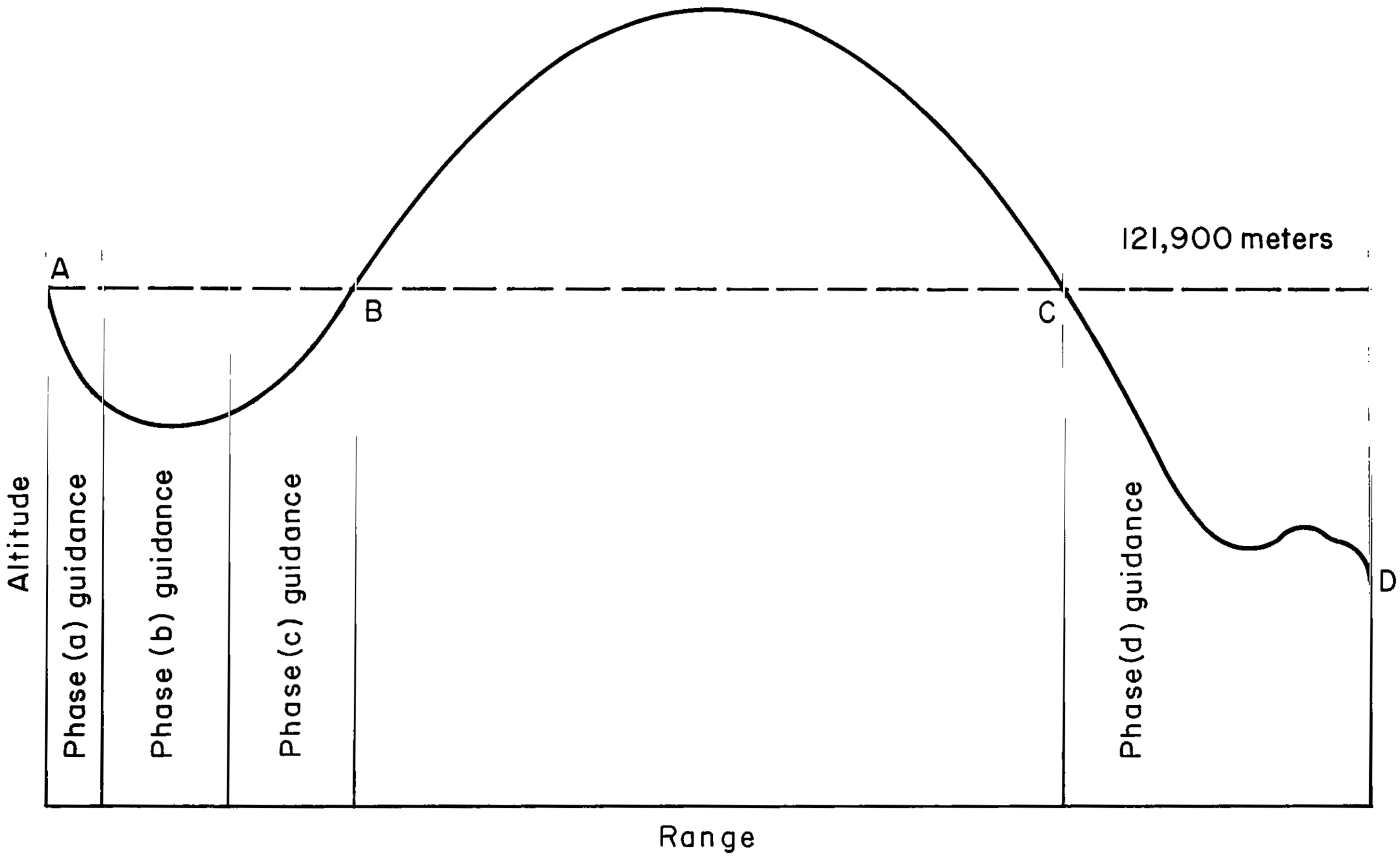


Figure 1.- Typical skip type reentry trajectory with guidance phases indicated for system being discussed.

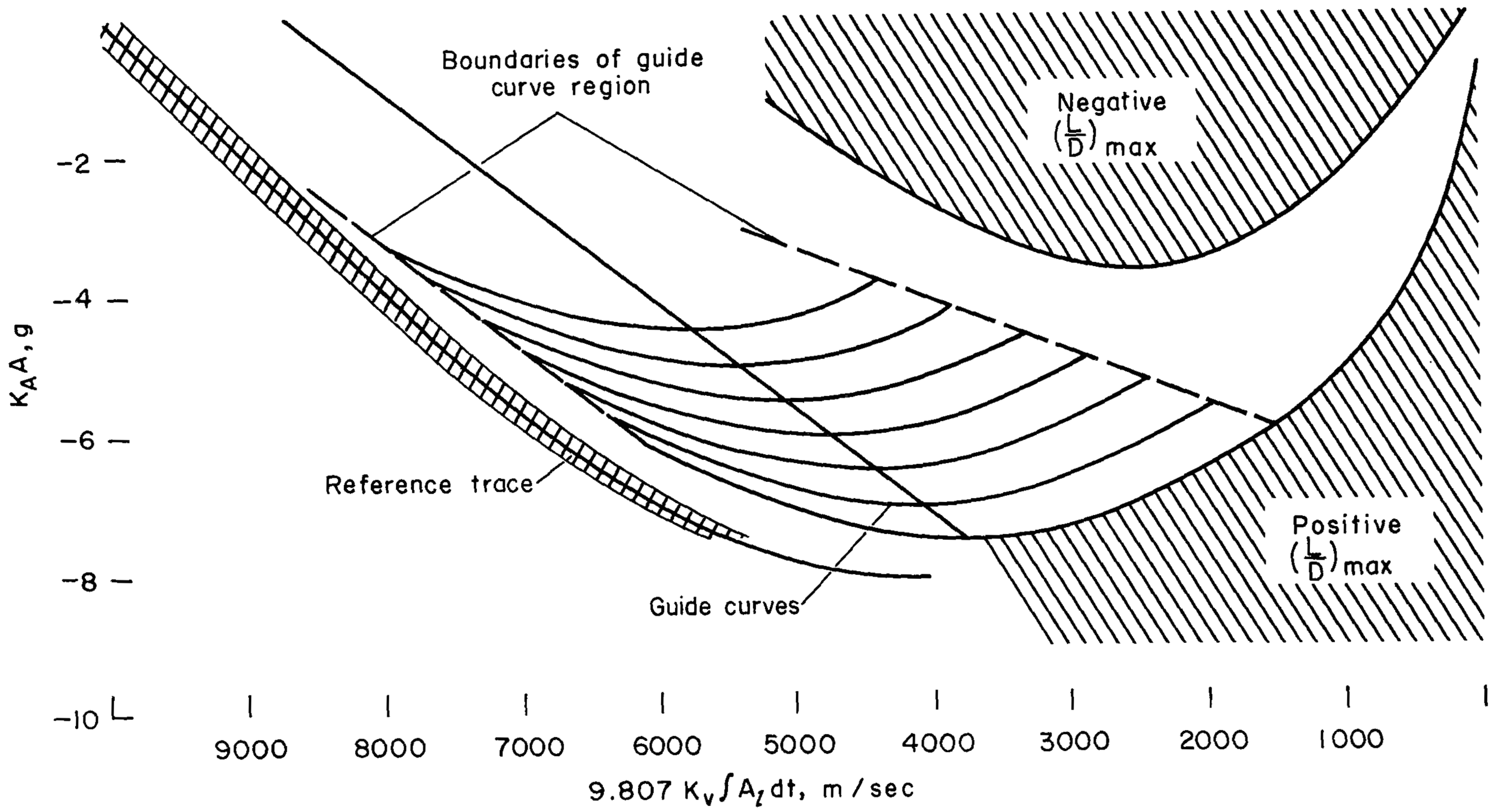
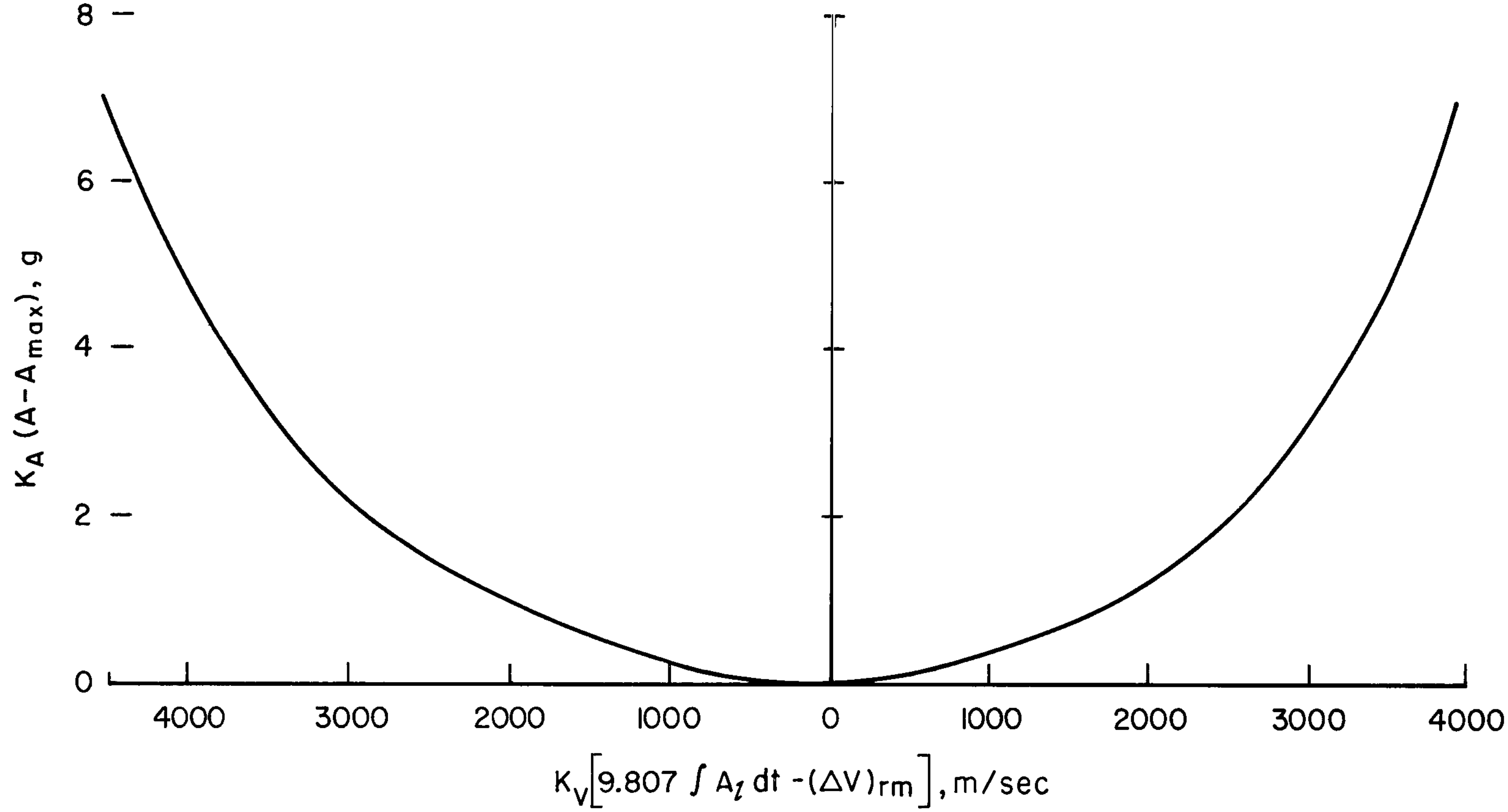
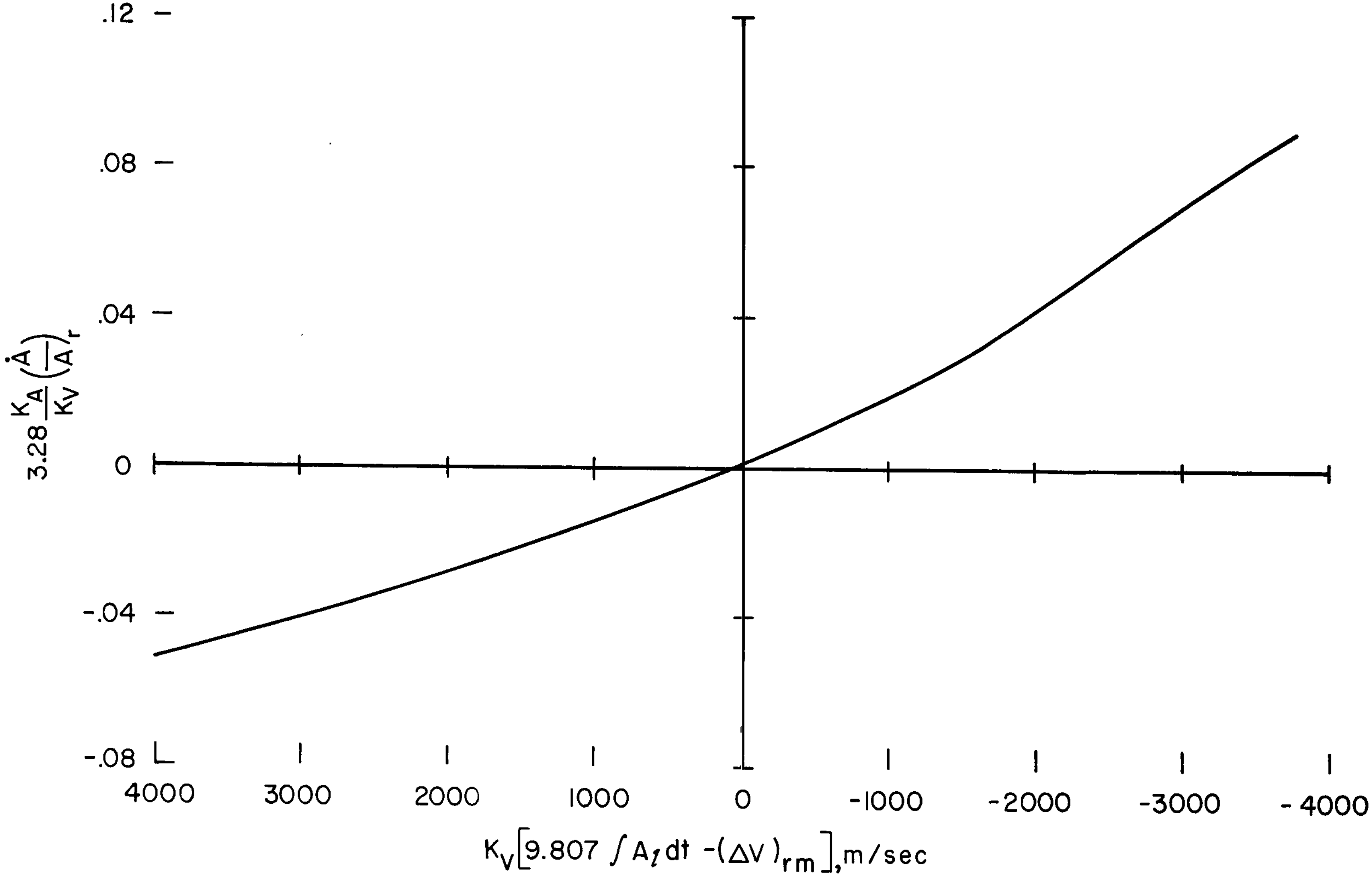


Figure 2.- Skip range control monitor display.



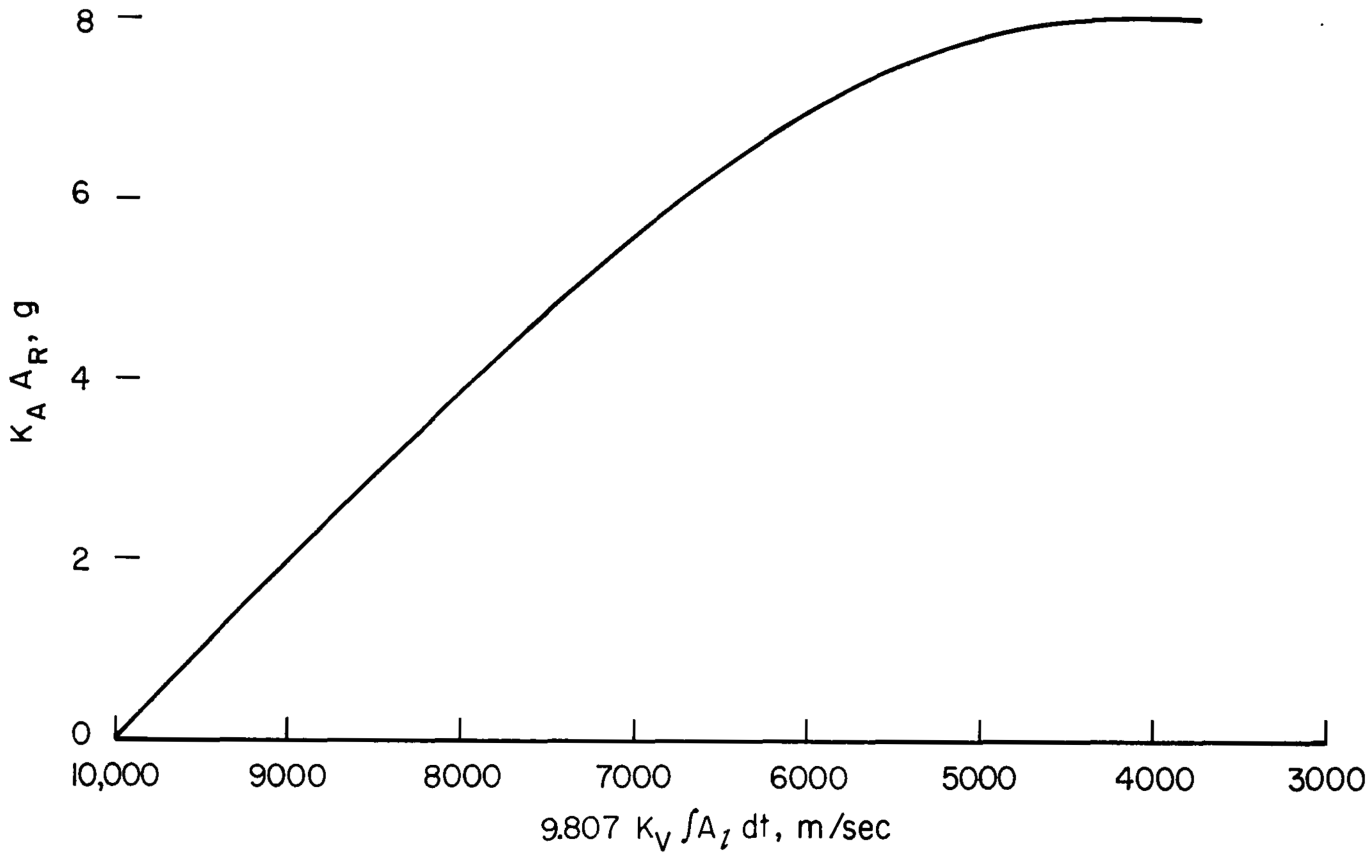
(a) $K_A(A - A_{max})$ versus $K_V[9.807\int A_l\ dt - (\Delta V)_{rm}]$.

Figure 3.- Complete guide curve.



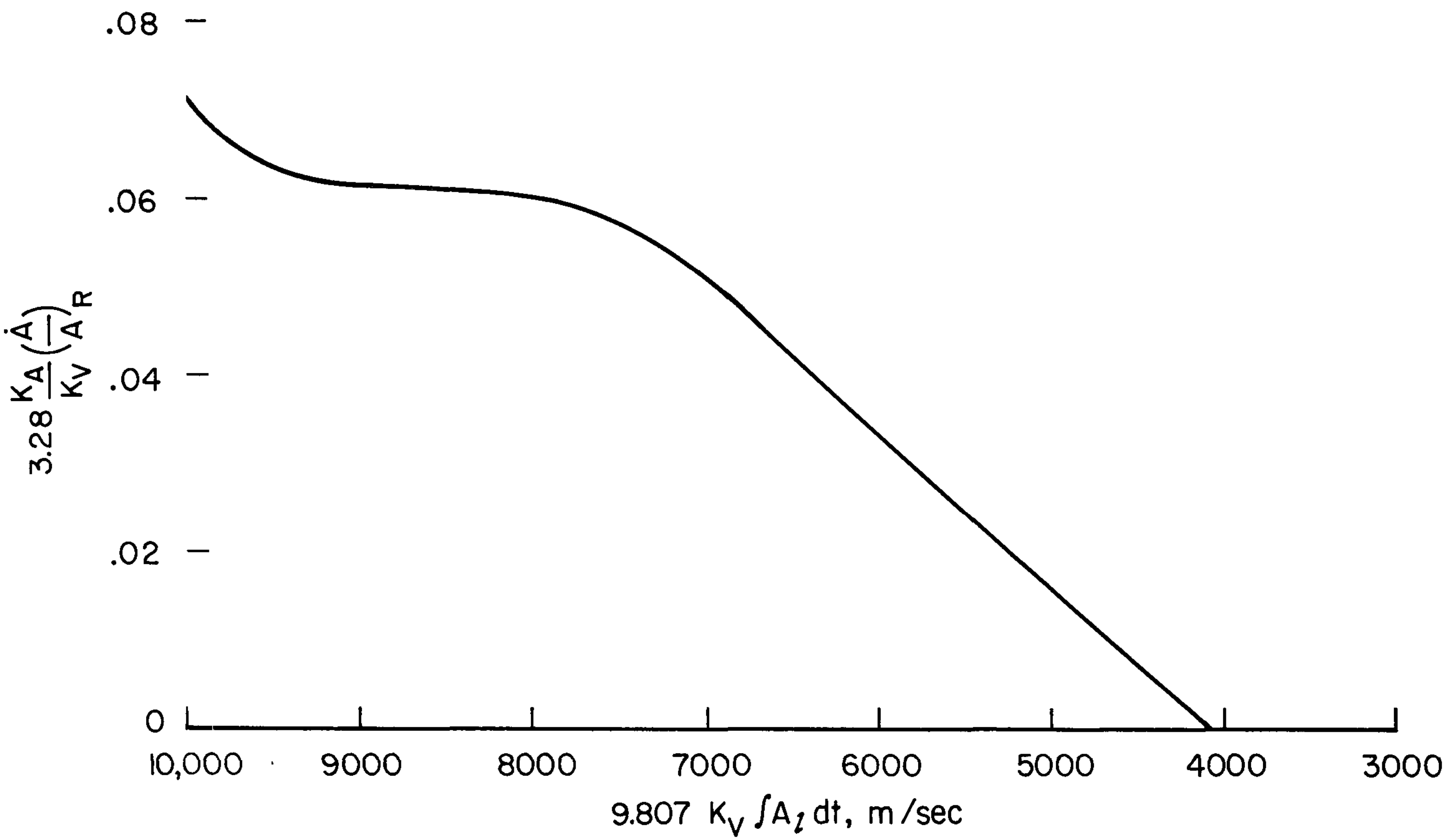
(b) $\frac{K_A}{K_V}\left(\frac{\dot{A}}{A}\right)$ versus $K_V[9.807\int A_l\ dt - (\Delta V)_{rm}]$.

Figure 3.- Concluded.



(a) $K_A A_R$ versus $9.807 K_V \int A_l\ dt$.

Figure 4.- Reference trace.



(b) $\frac{K_A}{K_V}\left(\frac{\dot{A}}{A}\right)_R$ versus $9.807K \int A_l\ dt$.

Figure 4.- Concluded.

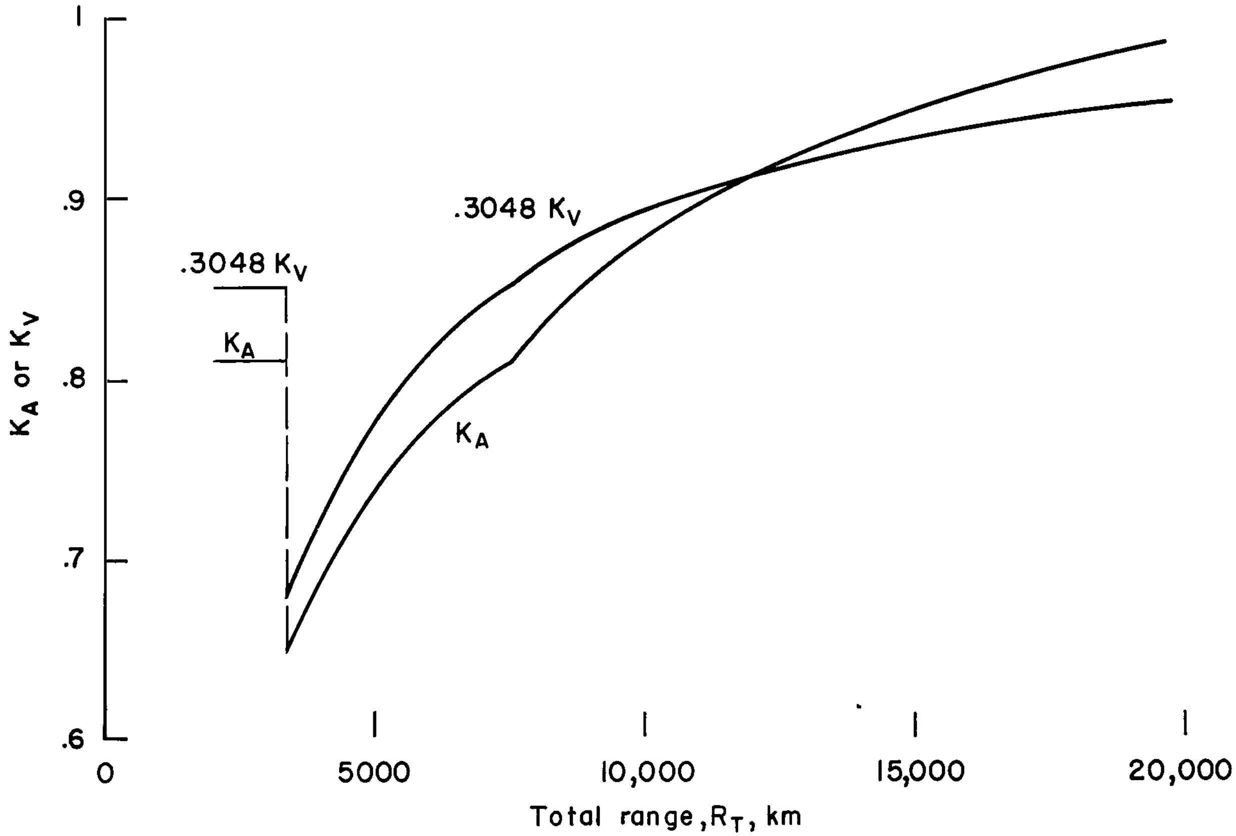


Figure 5.- Variation of K_A and K_V with total range.

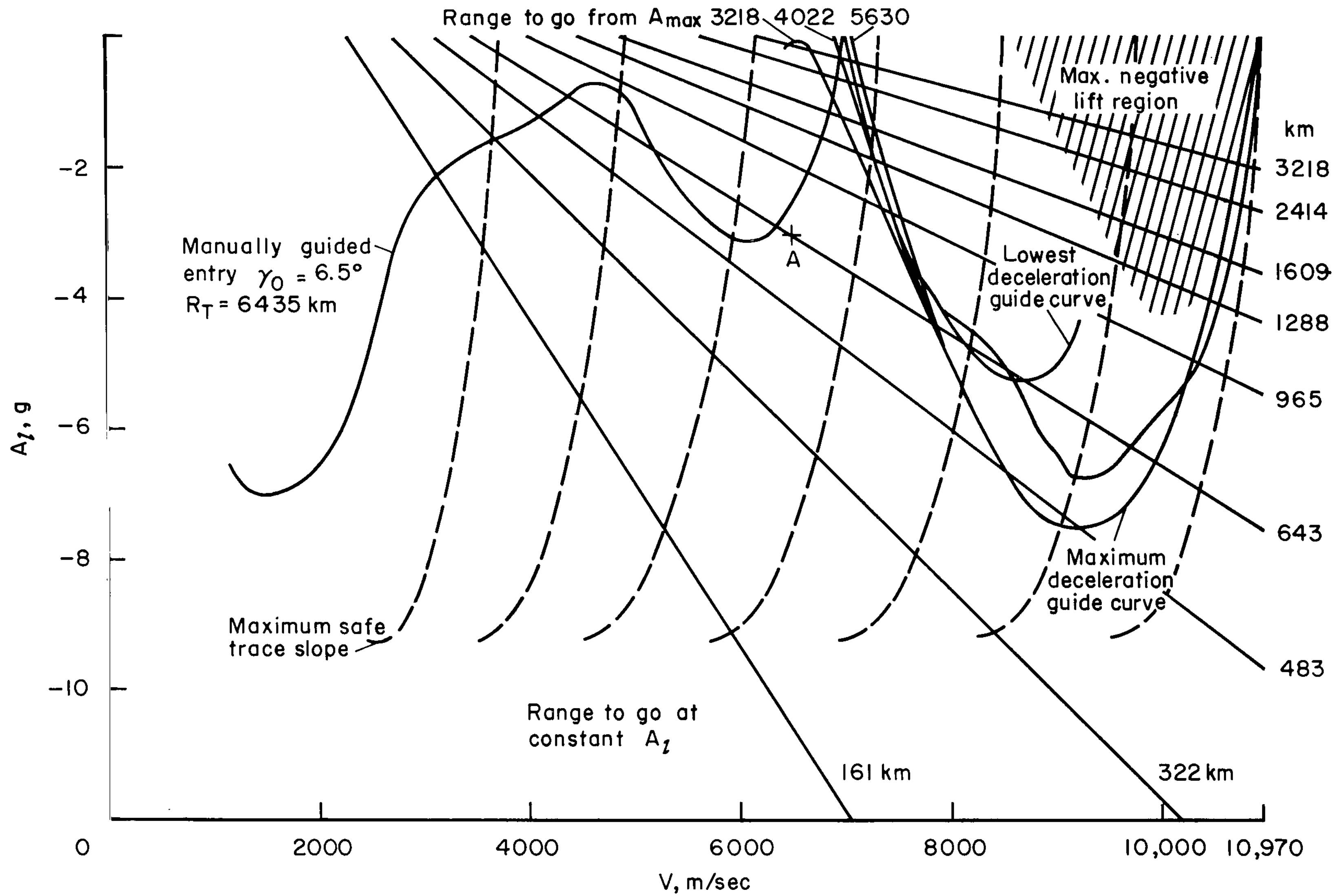


Figure 6.- Manual guidance display for short-range control.

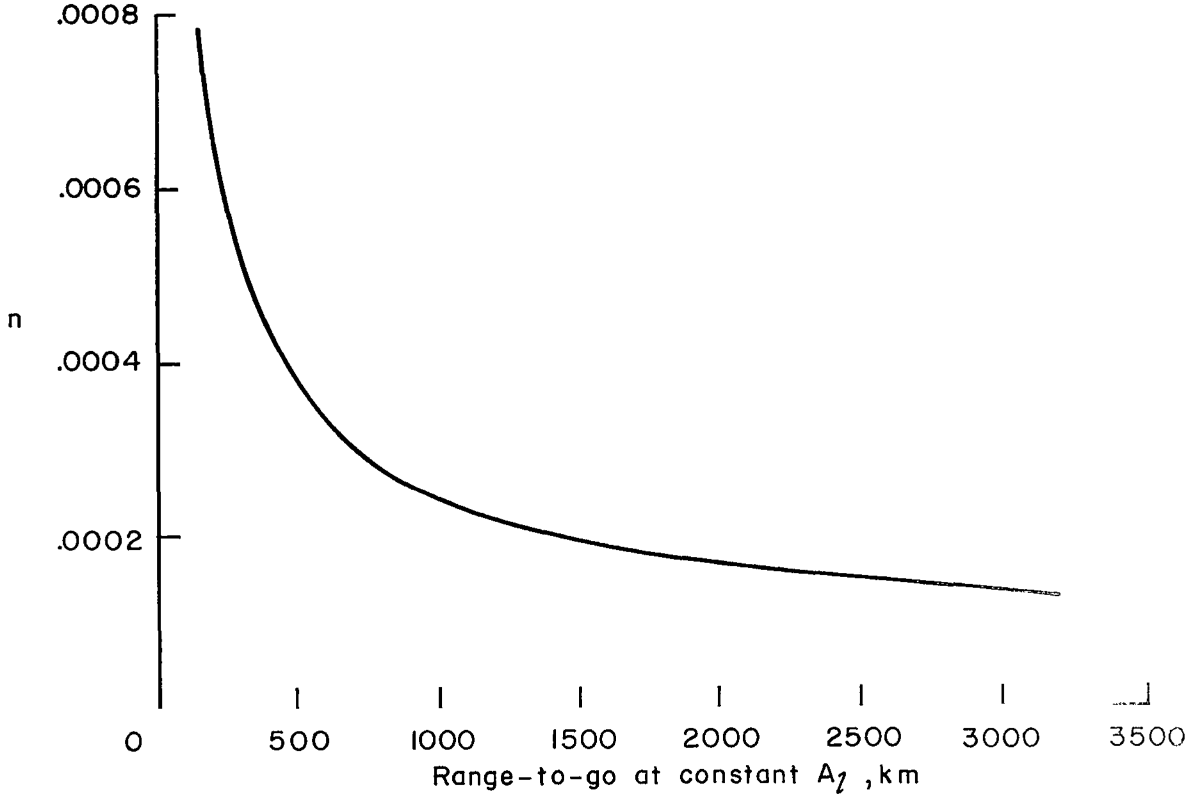


Figure 7.- Variation of n with R_{TG}.

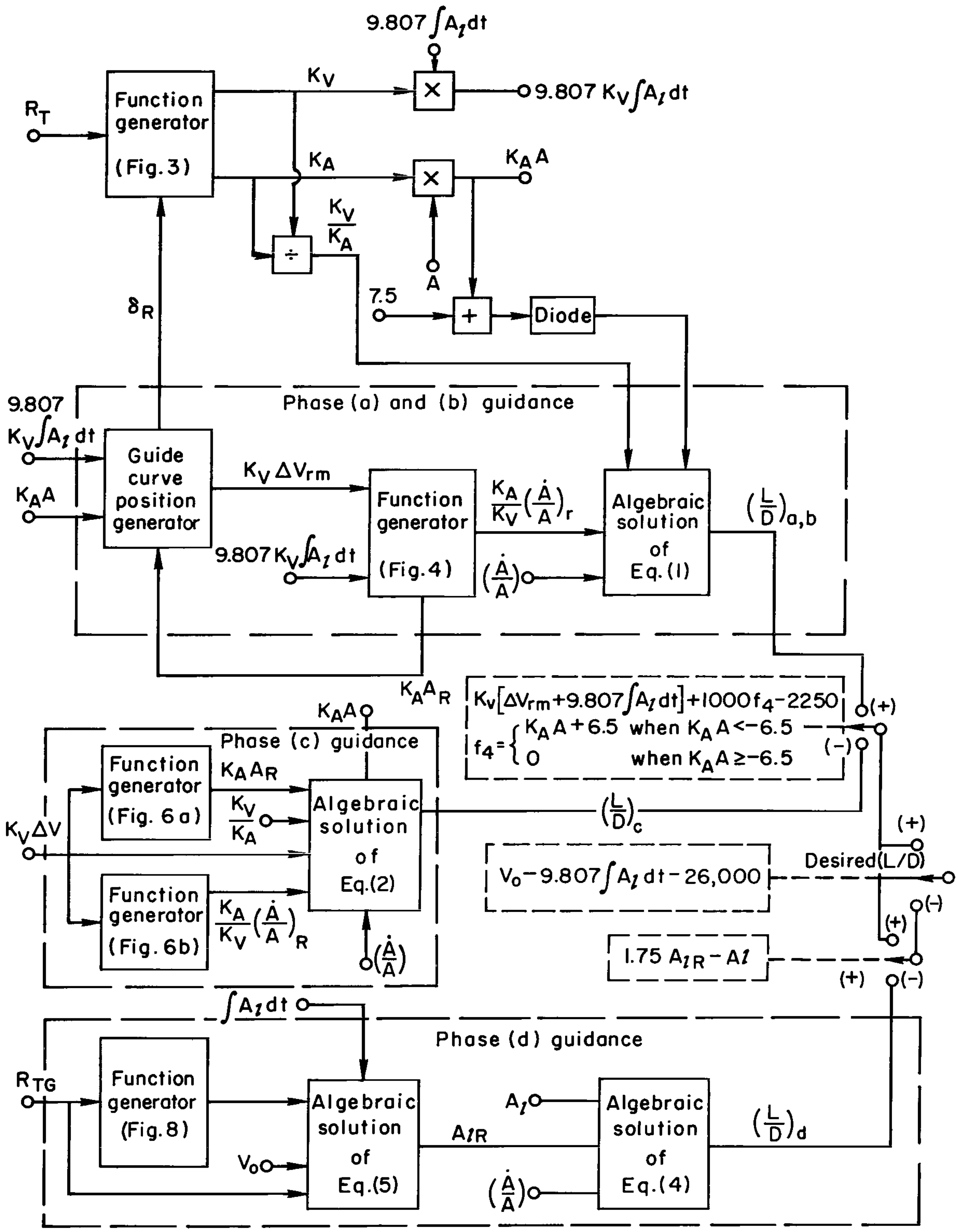


Figure 8.- Block diagram of automatic guidance system.

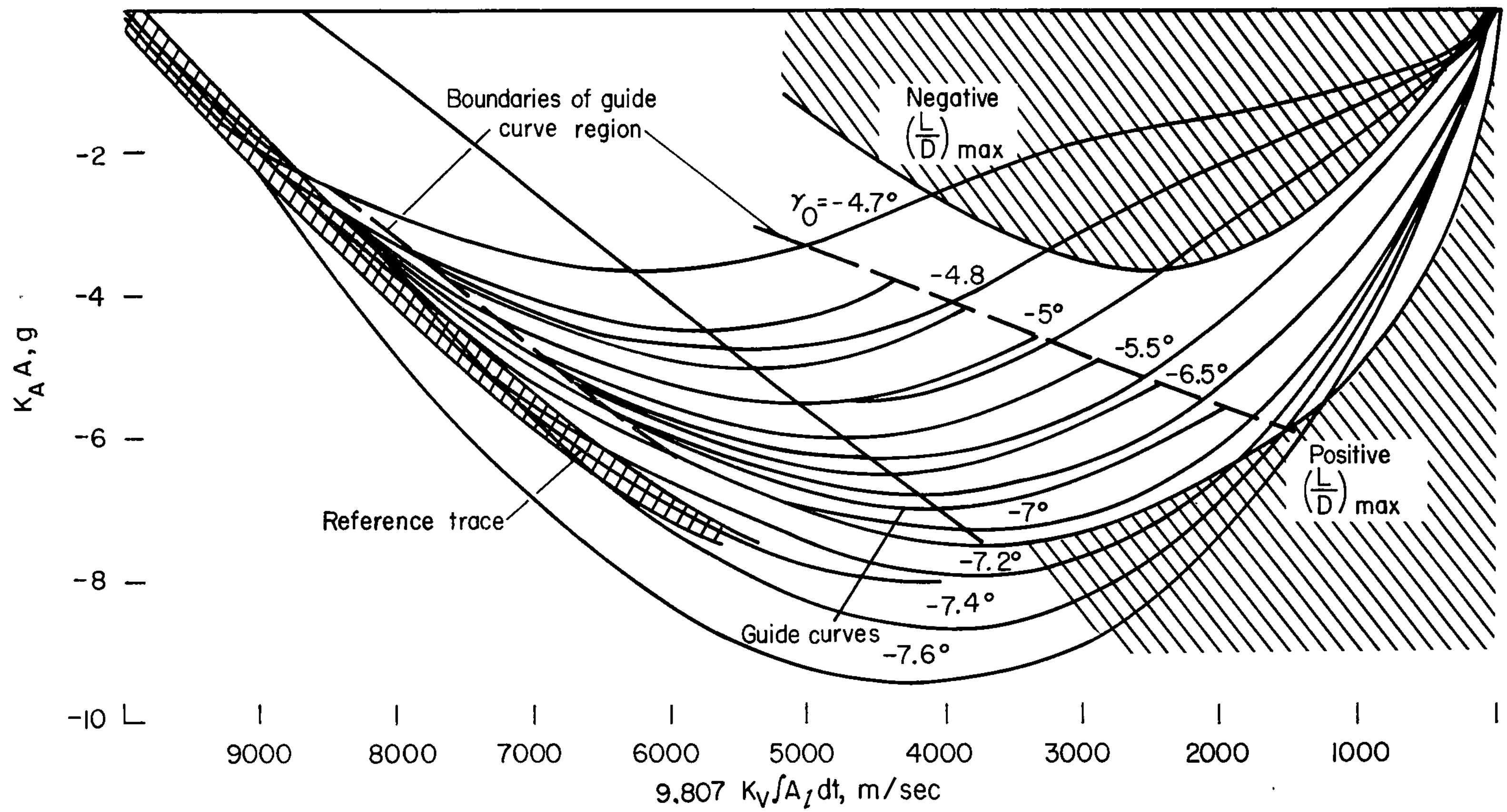


Figure 9.- Monitor traces for automatic skip-range control.

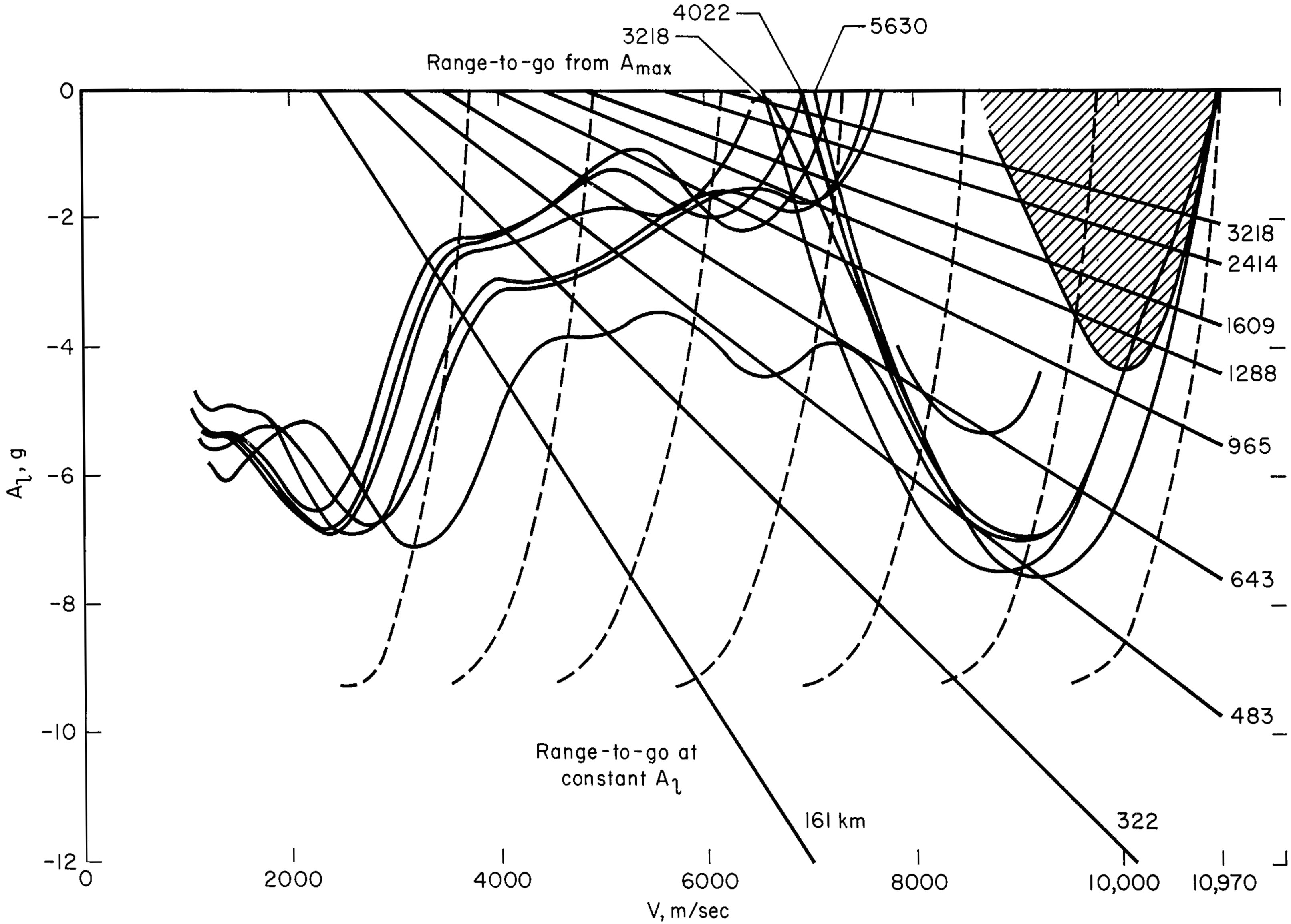


Figure 10.- Monitor traces for phase (d) and short-range automatic guidance.

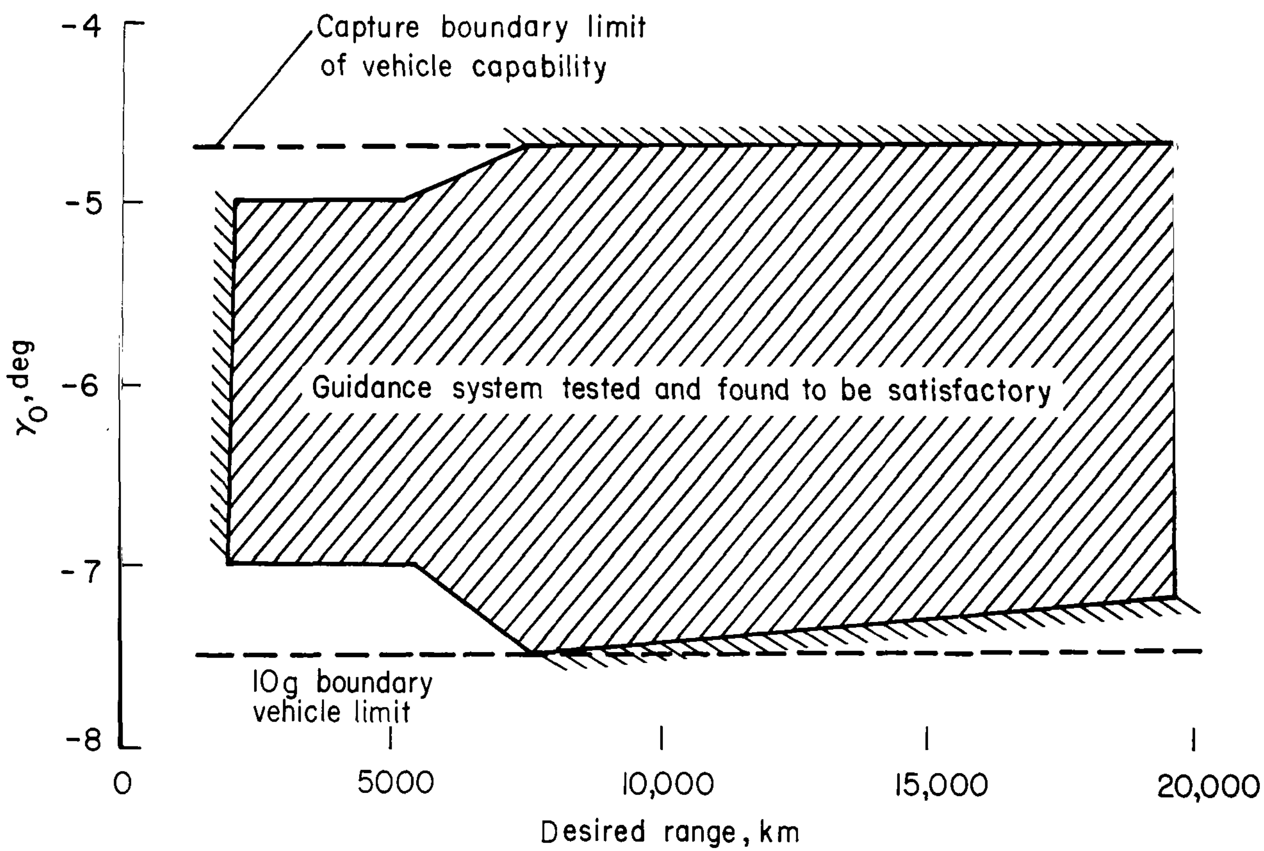


Figure 11.- Guidance system capability.

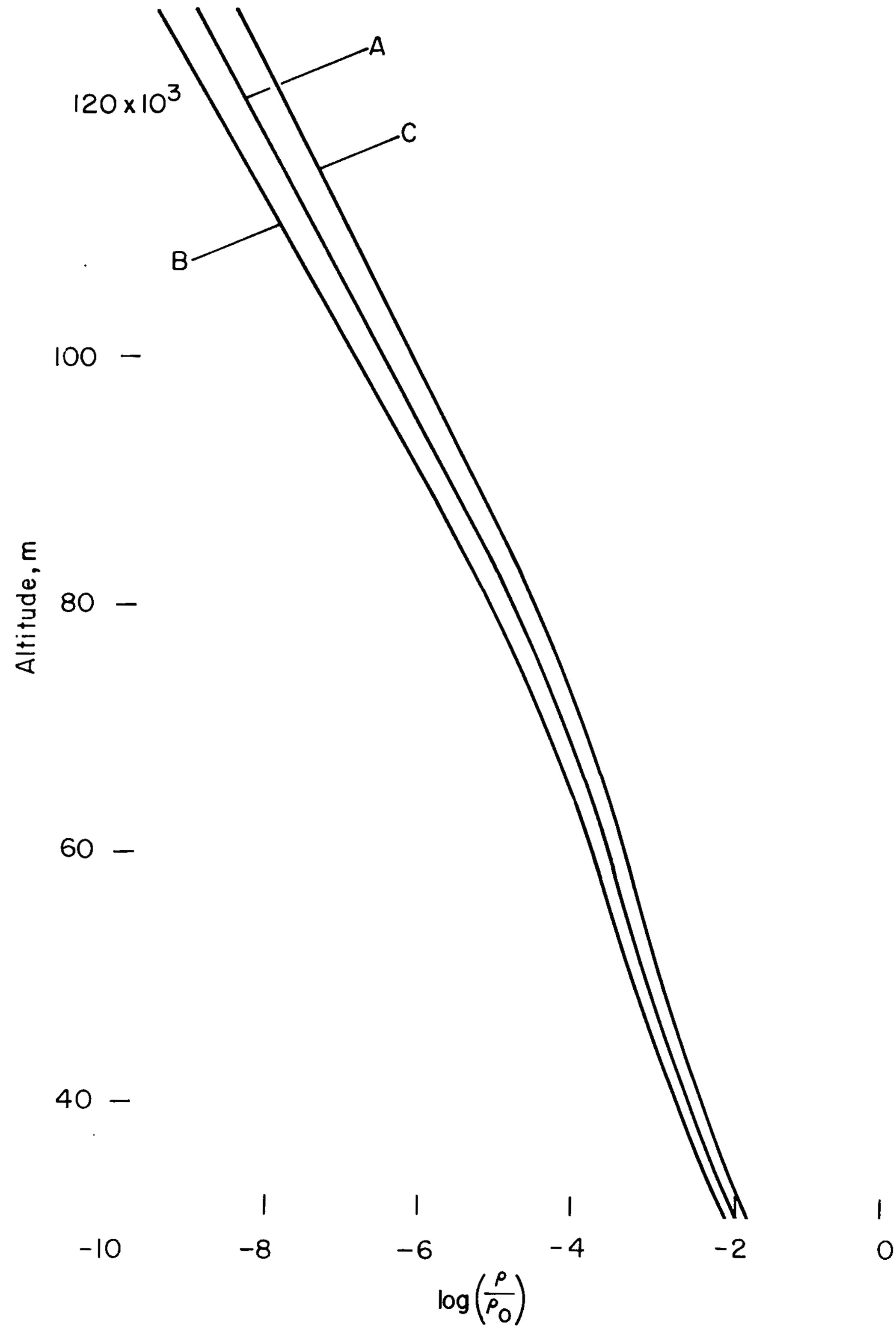


Figure 12.- Atmospheric density profiles investigated.

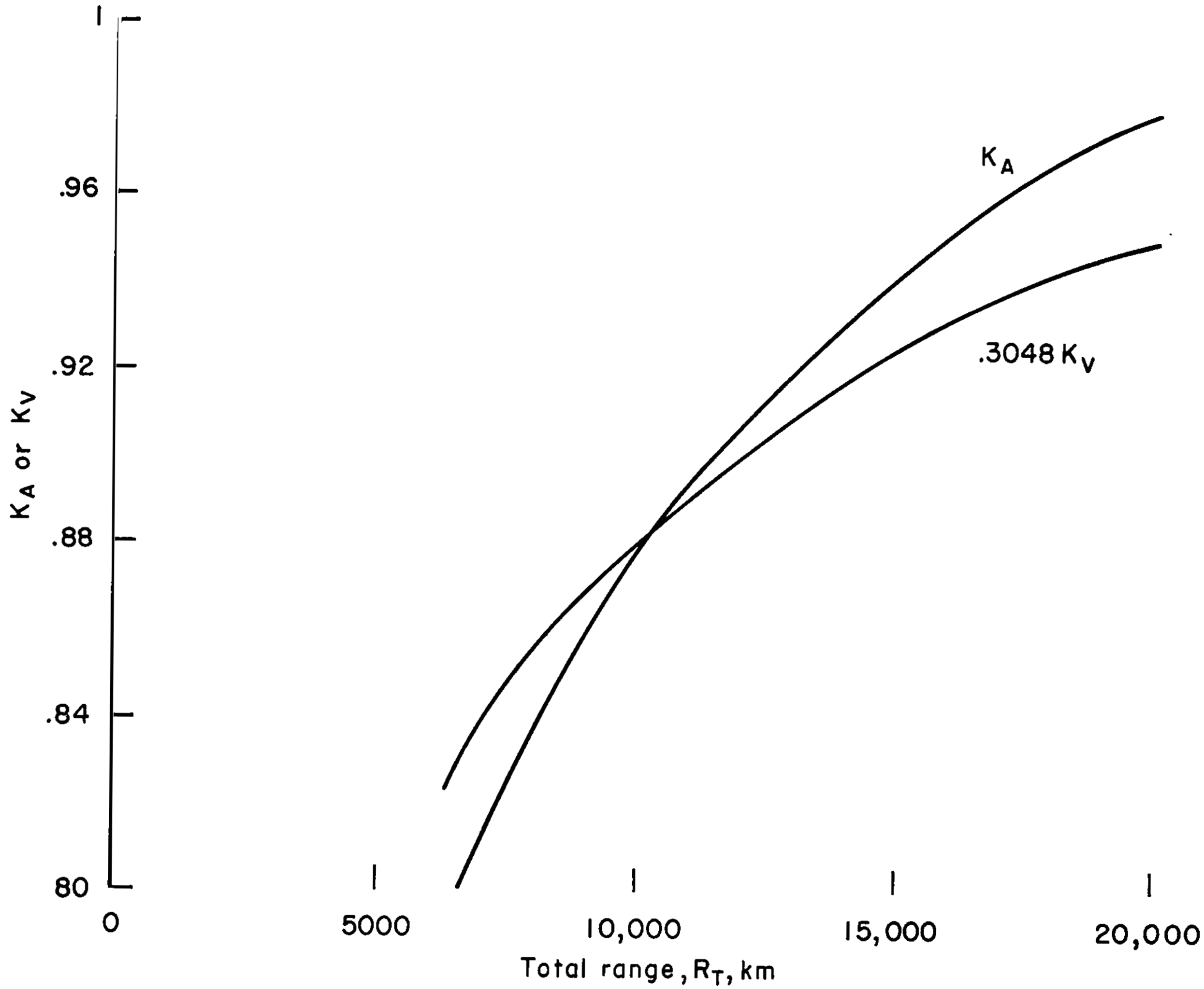


Figure 13.- Variation of K_A and K_V with range for manual guidance system.

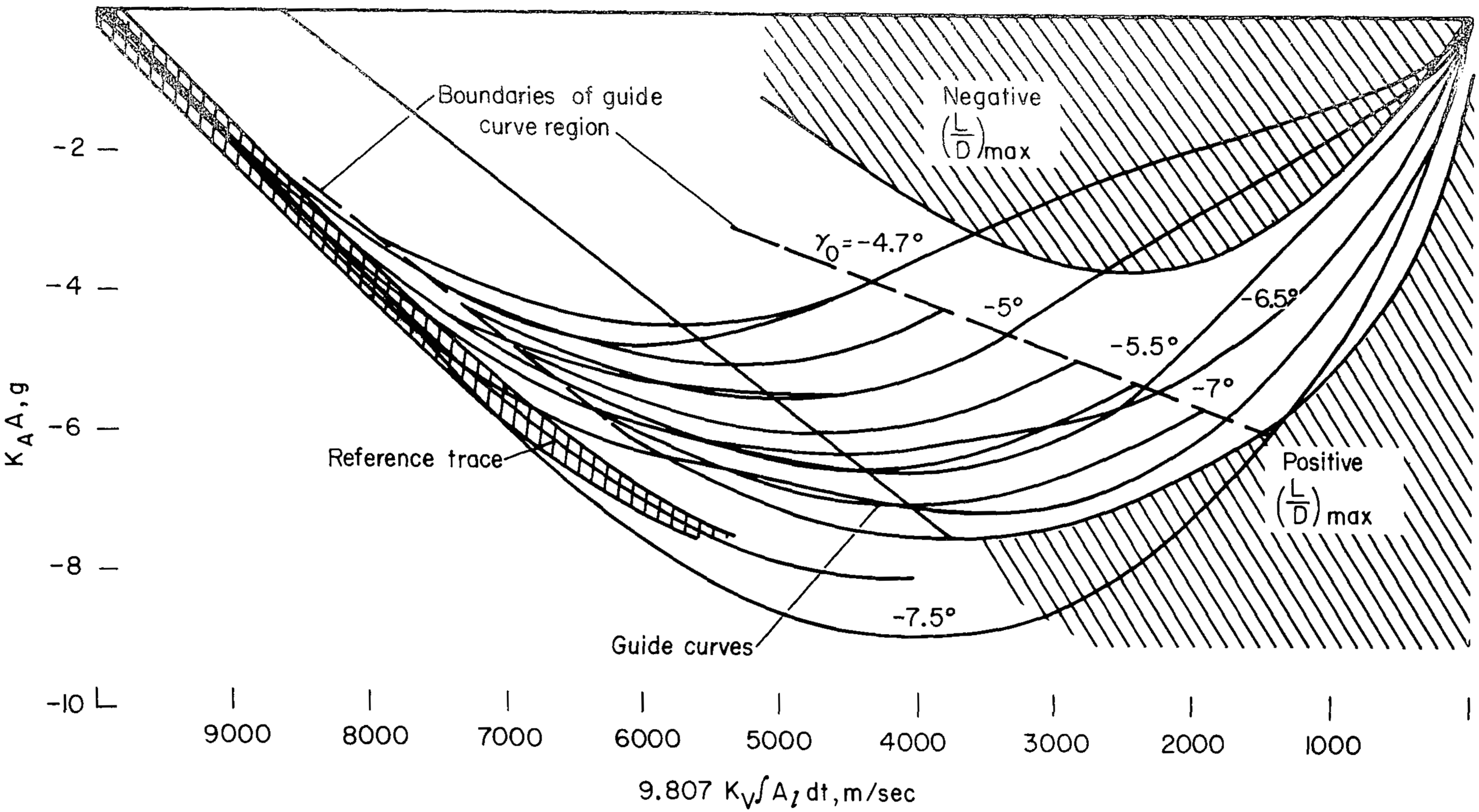


Figure 14.- Monitor display traces of acceleration histories during entries with manual control.

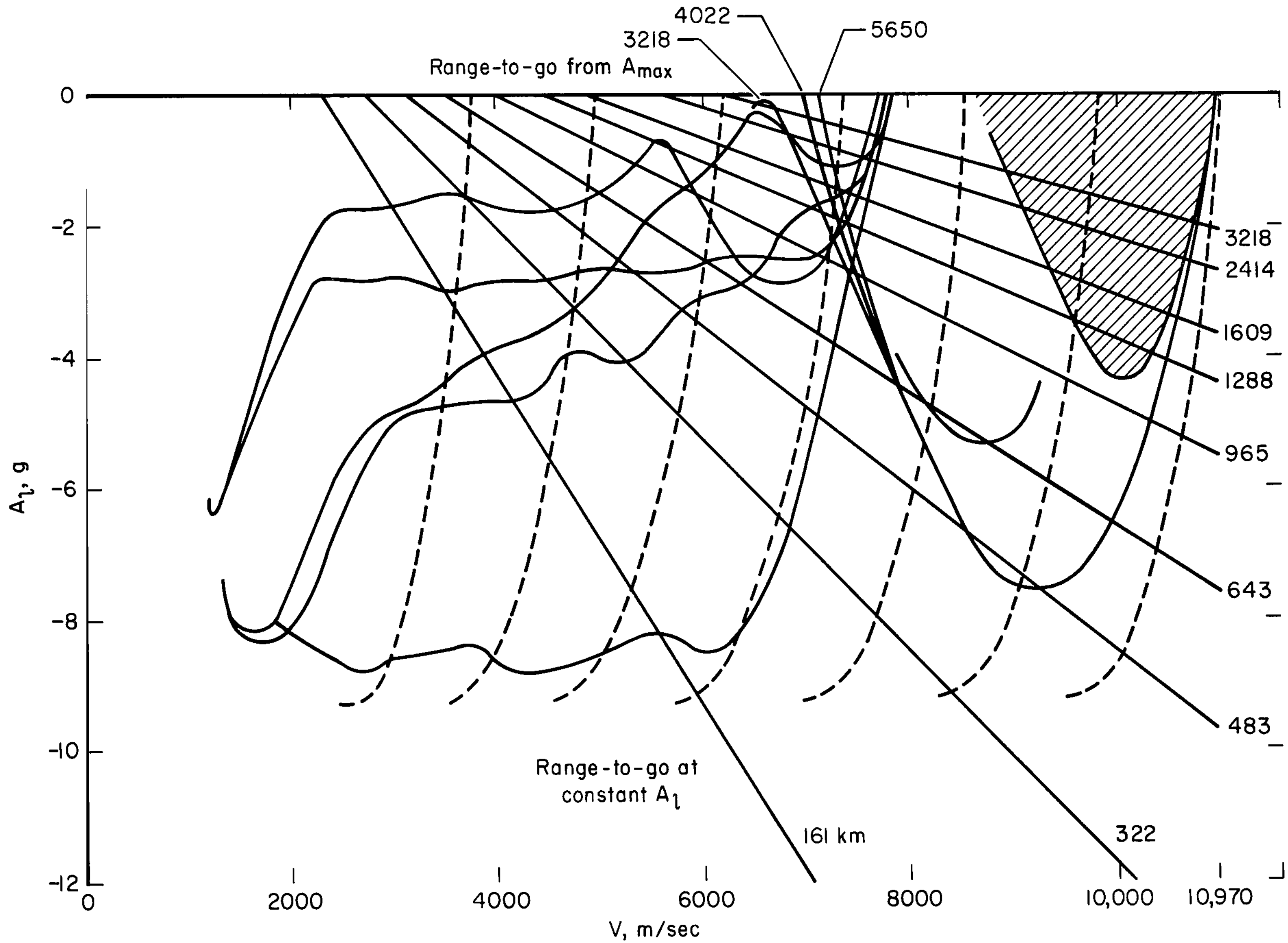


Figure 15.- Monitor display traces of acceleration history with manual guidance during second entry.

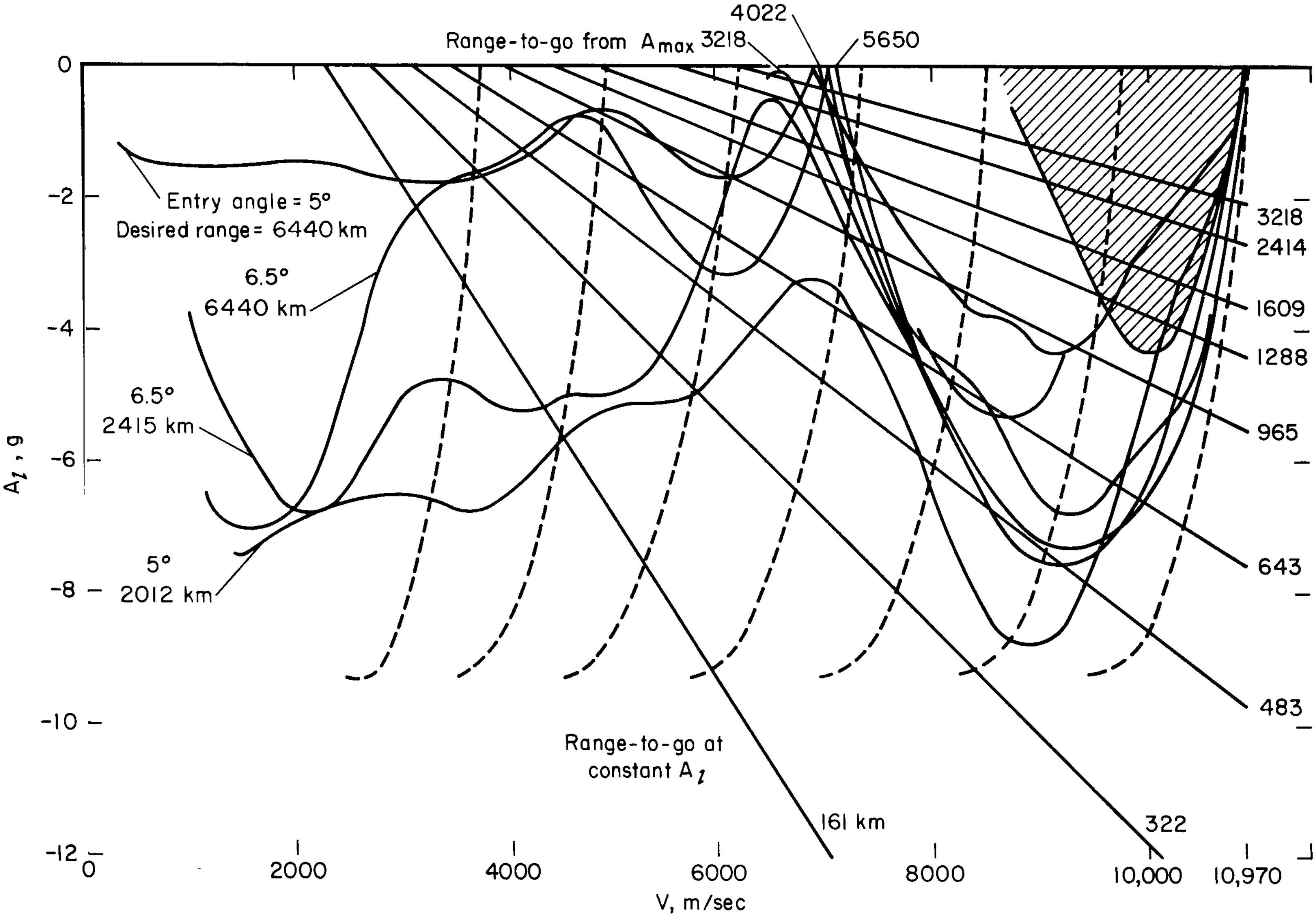


Figure 16.- Monitor display traces of acceleration history for short-range manual entries.

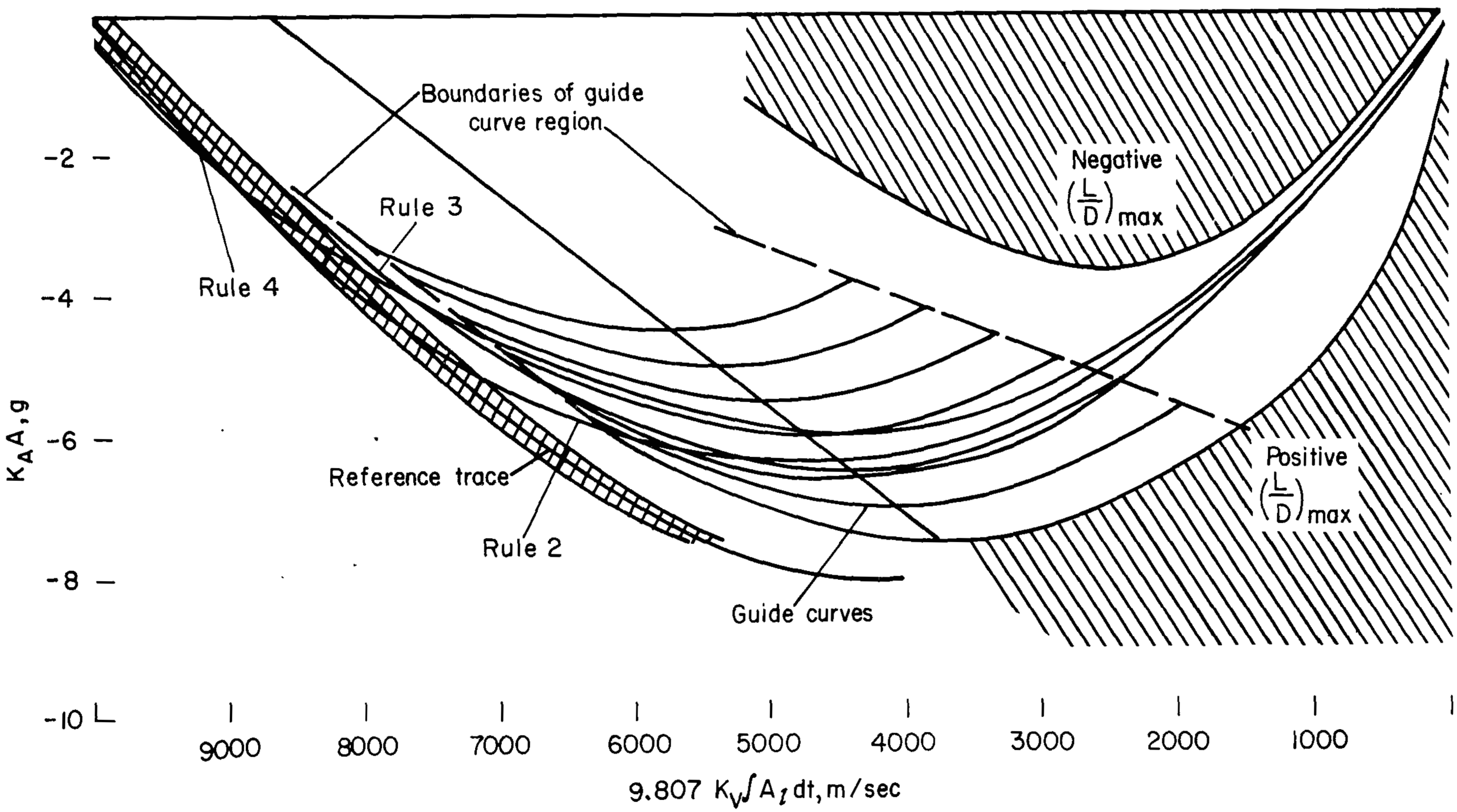


Figure 17.- Guidance system malfunctions illustrating violations of three monitoring rules.

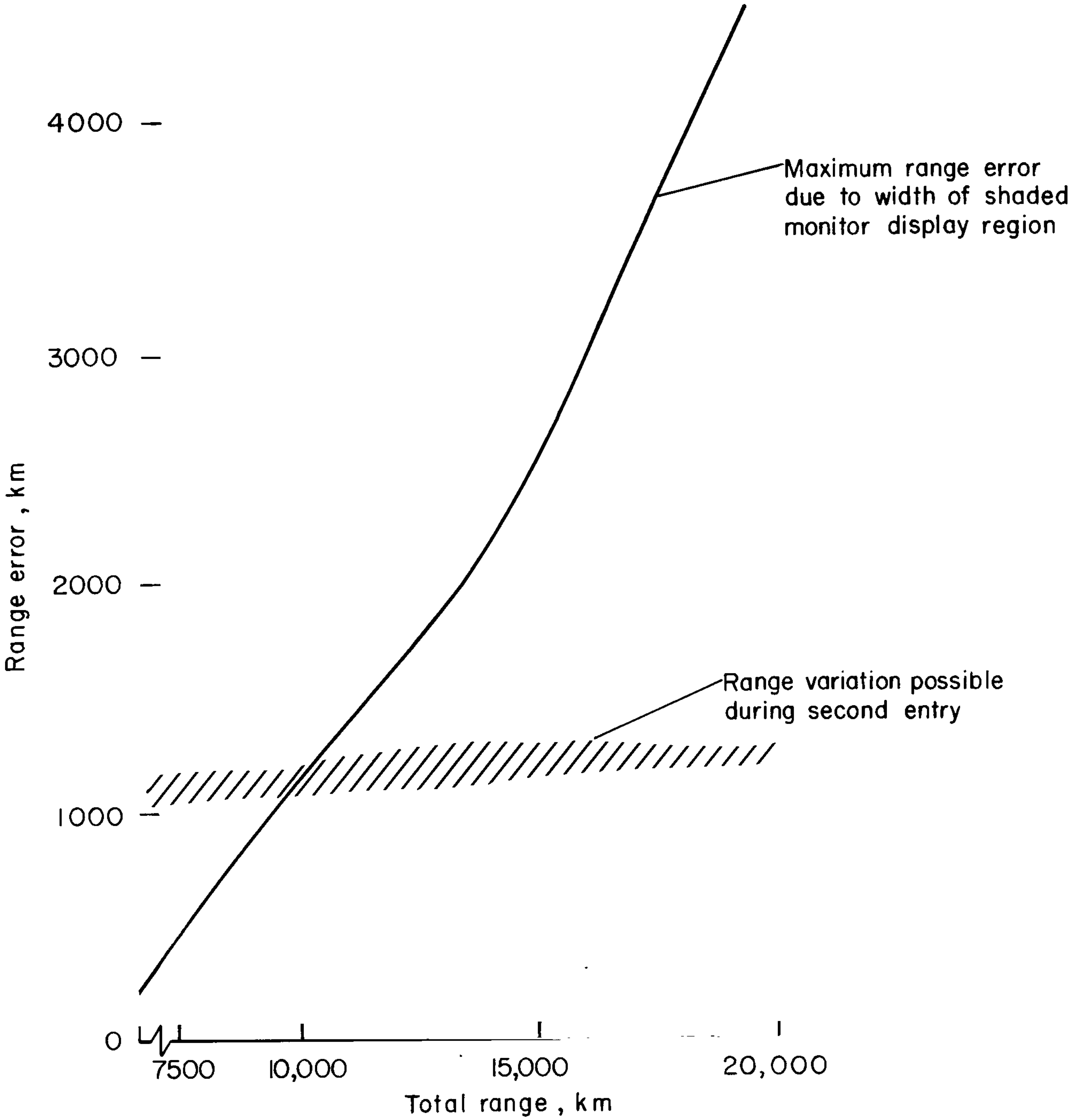


Figure 18.- Errors in skip range due to velocity errors at exit.

NASA-Langley, 1966 A-2294

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